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An integrated modeling system for environmental impact analysis of climate variability and extreme weather events in the San Joaquin Basin, California

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Abstract

This collaborative research project has two main objectives: to assess the vulnerability of water supply, water demand, water quality, ecosystem health and socioeconomic welfare within the San Joaquin River Basin as a function of climate variability and extreme weather events; and to provide guidance in the formulation of effective management strategies to mitigate the range of potential impacts due to climate variability and extreme weather. The project involves updating and advancing previous studies on climate change in California. Climate data are based on new Global Circulation Model output from the statistical downscaling that converts GCM climate forecasts into local weather forecasts. The project applies these climate data to perturb an existing 72-year historical hydrologic time series of the San Joaquin Basin to develop an integrated impacts analysis of climate change/variability on the water, economic and social resources of the Basin. Previous studies focused only on water resource impacts. A decision support system (DSS) is under development that will provide assistance to CALFED (a joint California State and Federal program designed to resolve water issues in the Bay–Delta) in water resource and ecosystem management of the San Joaquin Basin.

Keywords: Water resources; Decision support system; Impacts analysis; Hydroclimate; Climate change; CALFED

1. Introduction

Planning studies involving suites of complex models are often compromised owing to the inordinate amount of time devoted to data processing as the output from one model is manipulated to become the input to the next in sequence. This leads to frustration on the part of the decision maker, who is more apt to make mistakes if the time spent in data processing takes away from the task of setting up the modeling system to simulate the problem at hand. This is especially evident in the development of a modeling system for impact analysis due to perceived future climate variability and

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extreme weather events. Although the trajectory of global warming is still the subject of academic debate, the trend of increasing severity of weather events and increased climatic and weather variability is more generally accepted. Most projections of climate change are derived from computer simulation studies and generally suggest a global average temperature rise of between 2 and 5° over the next century for a doubling of carbon dioxide concentrations in the atmosphere. State and Federal water agencies in the arid west of the USA are beginning to appreciate the wisdom of contingency planning for future events that depart from the standard hydrologic time series developed from records over the past 100 years.

Climate variability and extreme weather resulting from global climate change may threaten the agriculturally dependent economy and fragile water dependent ecosystem in the San Joaquin River Basin of California and the Delta into which the Basin drains. The San Francisco Bay–Delta is the source of drinking water for over 20 million people who reside in cities surrounding the SF Bay, as well as coastal cities as far south as San Diego. The San Joaquin River Basin ranks among the most important agricultural regions in the world, with over 2 million acres of irrigated cropland and an annual output valued at $2.5 billion. Agricultural subsurface drainage and discharges from managed wetlands, generated within the San Joaquin River Basin and contaminated with salts and potentially toxic trace elements, are the single most important determinant of the ecological health of the Bay–Delta ecosystem. The concentration of contaminants in the San Joaquin River is affected by the relative timing of reservoir releases, primarily from the eastern side of the Basin, and drainage discharges from agricultural and wetland sources on the west side of the San Joaquin Basin. Future anticipated increases in climate variability and changes in the frequency and magnitude of extreme weather events will perturb the existing hydrologic system with the greatest impacts falling upon sectors most vulnerable to these changes.

Previous California water resources studies based on projected climate $2 \times CO_2$ scenarios using General Circulation Models (GCMs) and hydrologic models (Lettenmaier et al., 1989; Lettenmaier and Gan, 1990; Gleick, 1989; Dracup and Pelmulder, 1993), looked at large-scale planetary signals from Global Circulation Models (GCMs) and generated mean monthly streamflow from the weather patterns predicted by these models without fully resolving local basin-scale affects. These basin-scale effects can have important consequences for water storage and water quality in the San Joaquin River. In spite of this limitation, these studies concluded that the consequences of a global warming trend in California would be warmer winter storms, earlier runoff from the Sierra snowpack, and reduced summertime flow in tributary streams. Results also suggested that water resources in many arid environments, such as California's Central Valley, would become more vulnerable to climate variation than water resources in less arid regions. Several of the researchers hypothesized that basins with large numbers of tributaries would tend to increase damping of the signal generated by climate variability, resulting in smaller changes to project yield. The east side of the San Joaquin Basin contains several tributaries (Fig. 1) whereas the west-side of the San Joaquin Basin, which is in the rain-shadow of the Coast Range, has relatively few tributaries. Severe storms on the west-side of the San Joaquin Basin can produce extreme flooding events such as occurred in 1983, 1986, 1995 and 1997. These studies also suggest that the groundwater resource would become increasingly stressed as a result of increased pumping, brought about by decreased surface water availability. Increased stress on the groundwater system can result in decreases in the quality of pumpage as zones of high salinity are drawn down into underlying aquifers of higher water quality.

In general, changes in the timing of streamflow in the tributaries and San Joaquin River, resulting from perceived global warming trends, produce potentially severe impacts on water quality, aquatic productivity, species diversity, and species distribution. In instances where climate warming scenarios result in increased river temperature, fish spawning is negatively impacted. In these same scenarios, early snowmelt increases early spring streamflow which disrupts fish migration patterns. In the case of the anadromous Chinook salmon, the population was predicted to decrease by 50% in a $2 \times CO_2$ environment, partly as a result of possible changes in land use. Socioeconomic impacts resulting from changes in the timing of runoff include potential reductions in fulfillment of existing water rights and entitlements potentially leading to an increase in litigation and a decline in the equity of water allocation among competing uses.

2. Development of a decision support system (DSS)

Evaluation of the environmental and socioeconomic impacts of climate variability and extreme weather events requires the development of a computer-based modeling system to process the large amounts of information and data required for intelligent analysis and decision making. The goals of the current software

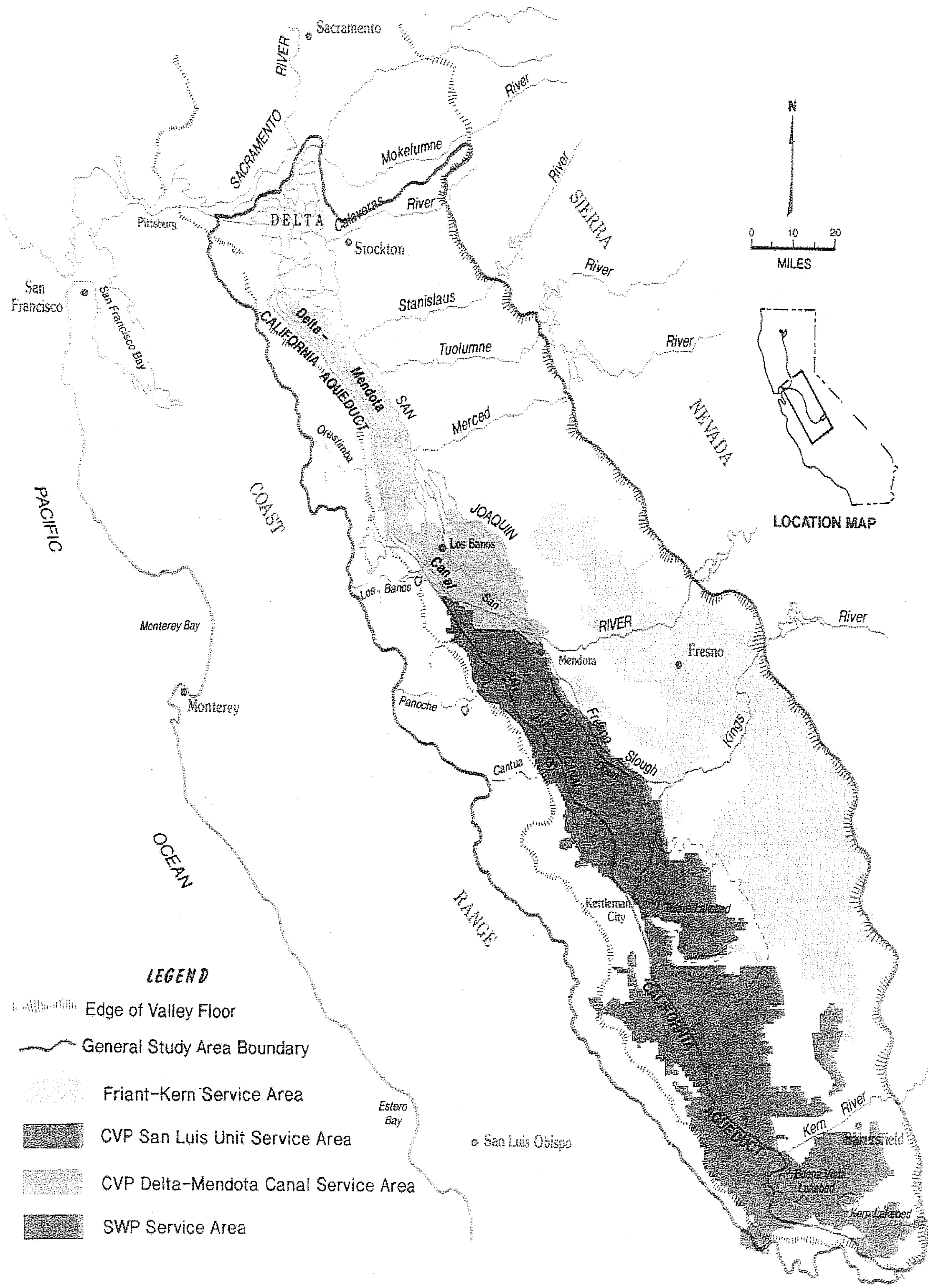

Fig. 1. Major Federal and State irrigation facilities and service areas.

development effort are to: (1) create a DSS that can assess the vulnerability of water supply, water demand, water quality, ecosystem health, and socioeconomic welfare within the San Joaquin River Basin as a function of climate variability and extreme weather events; and (2) use this DSS to provide guidance in the formulation of effective management strategies to mitigate the range of potential impacts.

To accomplish these goals, state-of-the-art mathematical models have been assembled from water agencies, the University of California and private consultants and are currently being incorporated in a fully integrated Decision Support System (DSS). Problem solving capability is enhanced in the DSS by the use of Graphical User Interfaces (GUIs) and the linkage to a Geographical Information System (GIS) for spatial data visualization and processing. The DSS takes advantage of recent advances in physically-based downscaled climate modeling to the sub-basin scale as well as the collective experience of the project team in using existing climate models, water supply allocation models, agricultural production and resource optimization models, fishery and ecosystem models, and economic analysis techniques. By utilizing planning models in daily use by participating institutions, this development effort, upon its completion, will provide a resource to these groups as part payment for their help in installing the models and verifying their function within the DSS. The target user community of the DSS will be water agencies and key representatives of various response and decision making sectors such as agricultural water districts, refuge managers and the informed general public.

3. Selection criteria

The criteria used in selecting models for this study

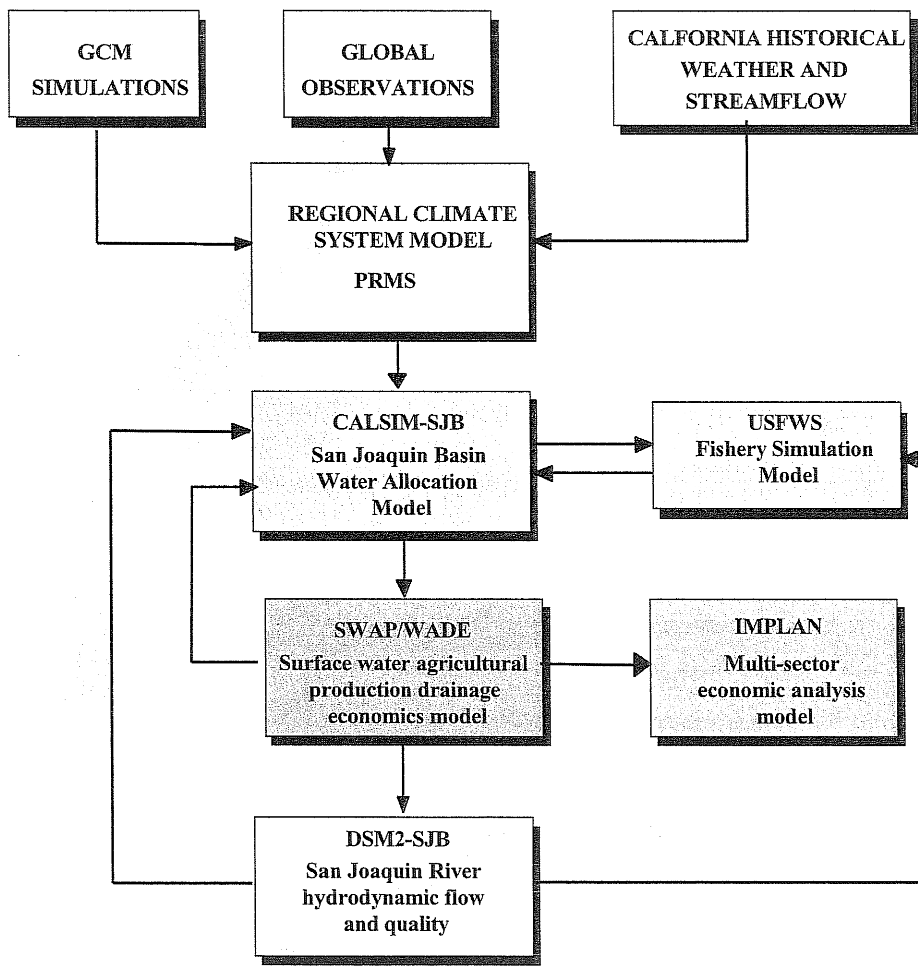

Fig. 2. Integration of models for vulnerability assessment of the San Joaquin Basin, California due to potential future variability and extreme weather events.

are: (a) general acceptance of models by the user community; (b) specificity of model data and scale to describe conditions in the San Joaquin River Basin; and (c) availability of model codes in the public domain. A schematic of our integrated modeling and analysis approach is provided in Fig. 2. The modeling and analysis approach is broken out into seven linked components: (1) weather and climate prediction; (2) drought likelihood analysis; (3) water supply allocation and streamflow; (4) agricultural production and management; (5) water quality; (6) fish ecology; and (7) socioeconomic impacts. Each of these model and monitoring systems are discussed in the following subsections.

4. Weather and climate simulations

Weather and climate simulations are performed by downscaling large-scale data derived from General Circulation Models (GCMs) to nested limited area models (Miller and Kim, 1996a). Output products include regional hydroclimate simulations (precipitation, snow budget, soil moisture, streamflow, temperature, wind, surface energy and water budgets) for short-term forecasts, seasonal-scale experimental predictions, and long-term climate scenarios (Miller et al., 1999). A pre-processor prepares input data from GCMs, global analysis, land surface geographical information, satellite and other remotely-sensed data. Physically-based process models include the coupled Mesocale Atmospheric Simulation and Soil–Plant–Snow model (Kim and Soong, 1996; Kim and Ek, 1995) a semi-distributed topographically forced hydrologic model (TOPMODEL: Beven and Kirkby, 1979), the distributed parameter hydrologic lumped (Sacramento Model: Peck, 1973), and a distributed parameter, hydrologic model with lumped hydrologic response units (Precipitation–Runoff Modeling System: Leavesley et al., 1983). The Regional Climate System Model is capable of producing 72-h advance forecasts with 6-h outputs at a 12-km spatial resolution for all California with area-weighted forecasts for the San Joaquin River sub-basins. The area-weighted forecasts provide important basin scale weather associated as forced by surface characteristics and atmospheric conditions. This unique capability will allow for more accurate forecasts and improved assessments. In addition to these short-term forecasts, experimental seasonal predictions and $2 \times CO_2$ simulations are being generated with the RCSM (Miller and Kim, 1996b, 1997; Kim et al., 1998, 2000; Miller et al., 1999, 2000). Seasonal predictions are needed for estimating spring season water supply and determining the likelihood of severe weather.

5. Water allocation and streamflow simulations

Output from the regional climate simulation models provide estimates of unimpaired streamflow which are processed to provide monthly flow volumes within the major east-side and west-side watersheds that drain into the San Joaquin River. These monthly flow volumes are the main input variables that drive the CALSIM-SJB model (California Water Allocation Simulation Model for the San Joaquin Basin). CALSIM-SJB is a hybrid linear optimization model which translates the unimpaired streamflows into impaired streamflows, taking into account reservoir operating rules and water demands exerted at model nodes, modified to reflect a year 2000 level of watershed development. CALSIM-SJB is in the final stages of calibration by teams of engineers from both State and Federal governments in a unique collaboration — in the past, modeling of State and Federal water projects in the California was performed independently. Calibration of this model involves setting penalty function weights to train the model to adherence to operating rules and constraints such as fish flow requirements, downstream water quality objectives and contract deliveries to agricultural and urban water districts. A matrix solver is used to determine the optimal monthly reservoir releases that meet all the system constraints. This model has distinct advantages over previous 'hard-coded' Fortran models in that it allows adjustments to be made in current operating rules and policies with relative ease by changing weights in the linear constraint equations rather than rewriting Fortran code. This is of particular benefit for contingency planning under future climate change scenarios where additional storage or changes in flood storage and release policies may be explored as ways of improving the reliability of water supply under forecasts of increased future demand.

6. Agricultural production economics and drainage salinity

An agricultural production economics and irrigation hydrology model SWAP/WADE is under development which will utilize available water supply predicted by the CALSIM-SJB model to determine crop production, groundwater pumpage and irrigation return flows within the San Joaquin Basin. Subsurface drainage flows from agricultural lands in the San Joaquin Basin have a significant impact on San Joaquin River water quality, especially during the summer months when the flow of the San Joaquin River is dominated by return flows from west-side agricultural sources. Drainage flows contain a number of environmental contaminants, including selenium, boron, nitrate, and salts. On average, these drainage flows contribute 60–70% of the salt and boron loading and 80–90% of the selenium loading to the San Joaquin River. In the absence of a means to export these contaminants, levels of salt and boron build up in the crop root zone and shallow groundwater aquifer. High levels of salt and boron in the crop root zone can significantly reduce crop yield, leading to reduced agricultural income and the predictable impacts on the socioeconomic welfare of farm workers and the rural economy.

A salinity model will be linked to the agricultural production and irrigation and drainage flow models to estimate the salts retained in the crop root zone after each irrigation season and the salt loading exported to the San Joaquin River. Agricultural production on the west side of the San Joaquin River is very sensitive to crop root zone salinity on account of the high levels of boron in the native soils. Hence, practices that attempt to achieve salt balance with the crop root zone will result in the transport of substantial salt loads to the San Joaquin River. Likewise, agricultural pumping, which will likely increase in circumstances where surface water deliveries are curtailed, will also lead to an increased salt disposal problem since groundwater supplies are invariably saltier than surface water supplies.

The Central Valley Agricultural Production Model (CARM) was developed by Howitt and others to estimate the impacts of policy, water resource supply and climate changes on irrigated agriculture in the Central Valley of California (Howitt, 1995). The Westside Agricultural Drainage Economics Model (WADE) was an outgrowth of this modeling effort and sought to estimate the quantity and quality of agricultural drainage resulting from policies to control selenium drainage from west-side sources. The WADE model comprised three optimization sub-models simulating seasonal agricultural production decisions, groundwater hydrology and groundwater water quality. The groundwater flow and water quality sub-models considered plant water requirements, groundwater pumping and agricultural tile drainage. The SWAP/WADE model currently under development will run with a monthly timestep to synchronize with the CALSIM-SJB model input and will provide monthly estimates of the volume and quality of agricultural return flows which will be directed towards a river flow and water quality model for water quality simulations and environmental impact analysis.

The agricultural production models can be utilized in a descriptive mode for performing vulnerability analysis and in a prescriptive mode for suggesting management strategies for mitigating the impacts of increased climate variability and more frequent extreme weather events. Unusual weather patterns, such as occurred in 1997 with El Nino produced run-off events that overwhelmed the water conveyance and distribution system within the watershed and lead to unusually high exports of salt, selenium and boron to the San Joaquin River. Increased climate variability and an increase in the frequency of unusual events could affect the long-term viability of growing certain agricultural crops on the west-side of the San Joaquin Basin.

7. River flow and water quality simulation

Drainage return flows generated by the agricultural production and groundwater models must be routed to the San Joaquin River in order to determine the impact of these activities on river water quality. A monthly mass balance model, the San Joaquin River Input–Output model (SJRIO) is currently used to account for contaminant loads exported to the San Joaquin River. The model performs a mass balance accounting of discharge, TDS, boron, and selenium for a 60-mile (96-km) reach of the lower San Joaquin River. The model calculates the load contributed from each source based on its flow and concentration using a mass balance accounting method. SJR flows and water quality are calculated for every tenth of a mile. Riparian diversions are currently estimated using three types of data: acreage irrigated by each pump, cropping patterns, and crop water use. Groundwater accretions or depletions and quality are currently considered steady state and are defined by the modeler for user-specified reaches of the river. Work is underway to replace the current model with DSM2-SJB, a one-dimensional fully-hydrodynamic extension of the State's Delta Simulation Model (DWR-DSM2). DWR-DSM2 simulates the complex hydrology of the entire Sacramento–San Joaquin Bay–Delta estuary and use of this model would allow recirculation of San Joaquin River water to the giant State and Federal pumping plants that export Delta water to agricultural water districts in the San Joaquin Basin, as well as coastal cities such as Los Angeles. San Joaquin River water, with its high concentrations of salts and trace elements, is less attractive to municipal and industrial users because of the high cost of removal of these contaminants in water treatment facilities.

Accurate forecasting capability is important in both the San Joaquin River Basin and the Bay–Delta, on account of water quality based standards and objectives that dictate actions such as export pumping to the California Aqueduct, west-side agriculture and the Los Angeles Basin. The linkages made between climatic, hydrologic and water quality models in this DSS can assist management of water quality in the San Joaquin River Basin and Bay–Delta. The Regional Climate Simulation Model currently provides 6-h predicted run-off and streamflow into the San Joaquin River and its tributaries during the winter and spring months to assist water quality forecasting.

8. Aquatic ecosystem and fishery adaptation management

The complex ecology of the San Joaquin Basin is highly dependent on the flow, water quality, temperature and the timing of flow releases along the San Joaquin River and its tributaries. A salmon fisheries model is under development within the Federal Fish and Wildlife Service, which employs a functional relationship between these key factors to estimate impacts on the fishery. Validation of these models is being aided by the support of adaptive management programs in the State — these are techniques of continuous assessment of a resource and application of interventions to optimize the ecological health and productivity of the resource. For example, real-time monitoring of hydrologic parameters such as in-stream flow, water quality parameters such as temperature and salinity, and biological parameters such as fish population and diversity in the San Joaquin River and its tributaries, allow the estimation of optimal levels of these environmental factors to sustain the fishery. Hence, proposed reservoir operations under climate change scenarios, obtained from the model analysis using CALSIM-SJB, can be associated with impacts to the health and species diversity of the fishery. Knowing the relationship between environmental conditions and species health and diversity suggests interventions that might be considered to mitigate these impacts. Because of the importance of the fishery to the State of California and the fact that fishery flow obligations comprise many of the constraints built into the CALSIM-SJB model, a feedback loop allows fishery impact analyses to adjust reservoir operating decisions made in the earlier CALSIM-SJB model — hence, improving the realism of simulations.

9. Socioeconomic impacts and analysis

Climate change may increase the incidence of extreme events, such as the December 1998 sustained freeze in the San Joaquin Valley which may have destroyed as much as 60% of the valley's citrus crop, resulting in economic losses as high as $650 million to the local economy. Crop failure affects not only the farmer, but also eliminates seasonal farm jobs and reduces income to service sector businesses that rely on the agricultural industry. Floods and multi-year droughts also affect crop production and result in negative socioeconomic impacts to the region and State. Changes in crop selection by farmers to cope with changes in climate can also result in socioeconomic impacts as a result of shifts to less labor-intensive crops. There is a multiplier effect, such that losses in one sector are magnified at the State and even National level, affecting tax receipts in both State and Federal treasuries and reducing funding for social welfare and health programs.

A linkage will be made within the DSS to the county-level IMPLAN input-output economic model to measure the regional economic impacts for the San Joaquin Basin. The IMPLAN input–output model allows the construction of input–output models for counties or combinations of counties for any location in the United States. Input–output data are the economic accounts of any given region and show the flow of commodities to industries from producers and institutional consumers. The accounts also show consumption activities by workers, owners of capital, and imports from outside the region. IMPLAN contains 528 sectors, representing industries in agriculture, mining, construction, manufacturing, wholesale and retail trade, utilities, finance, insurance and real estate, and consumer and business services. The model also includes information for each sector on employee compensation, proprietary and property income, personal consumption expenditure, federal, state, and local expenditure, inventory and capital formation, and imports and exports. The model can be used to produce accurate estimates of the impact of changes in expenditures in specific local activities on employment and income in any given year. The analysis of regional economic impacts uses the model to calculate multipliers for each sector at each site for procurement, wage, and salary expenditures likely to occur.

10. Data integration architecture

In order to seamlessly link the various models that make up the DSS, a unique system of model integration software is being employed (Leavesley et al., 1996). The Modular Modeling System (MMS) is a framework of pre-processing, model run and post-processing libraries that allow individual modules to be 'shrink wrapped' and, hence, treated as objects within a Decision Support System. The MMS was originally conceived by the US Geological Survey in cooperation with Boulder's Center for Advanced Decision Support for Water and Environmental Systems (CADSWES). Since the initial development the system has been applied to numerous DSS applications within the US and internationally. The MMS has three major components: a pre-processor, the data model and a post processor. A system supervisor, which takes the form of an X-window graphical user interface (GUI) provides the end user with access to all the components and features of MMS.

The pre-process component includes software designed to input, analyze and prepare spatial and time series data for use in the various model applications. Spatial data analysis is accomplished through calls to GIS libraries such as ESRI Arc-Info. Databases are used to store spatial and time series data and provide the interface between the pre-process and model components. For the current DSS application, Microsoft Access was chosen as the relational database for the models and the US Corps of Engineers Data Storage System (HEC-DSS) for time series data.

The model component includes tools written in Java and C programming languages to selectively link process modules to build each module within the DSS and to perform the variety of simulation tasks called for within the DSS and delegated to each model. X-window and graphical techniques are used to provide this interaction. An interactive model builder interface (xmbuild) selects and links models within the DSS. Once a model has been 'built' within the DSS, no further invocation of xmbuild is necessary. The X-windows GUI, which is used for model preparation and execution, contains a series of pull-down windows which allow the selection and editing of the individual model data and parameter files, selection of a number of model execution options including spatial visualization, optimization or sensitivity analysis, and the selection of graphical and statistical analysis packages to analyze model results.

One graphical tool allows the user to display output in up to four separate windows during a model run — any variable declared within a module can be plotted. The post-processing module also links to GIS post-processors, such as ARC-INFO and GRASS. Results can be forwarded in HPGL or postscript formats for printing. A schematic diagram of the system components of Leavesley and coworkers' Modular Modeling System (MMS) is shown in Fig. 2. The system of linked models that will be linked through MMS, as illustrated in Fig. 3. In Fig. 3, the sequence of models within the DSS is shown together with the main feedback loops — where the results of one model are fed back to a prior model in sequence so as to update certain parameter values that are of importance. The number of iterations of these feedback loops will be determined by setting up an error criterion and test condition within the DSS. An example of this feedback loop is provided by the series of triggers contained within CALSIM-SJB code. Projections of fish populations are based on the prevailing flow, temperature and salinity conditions within the San Joaquin River. These conditions are calculated after projected water allocations from CALSIM-SJB are processed by the SWAP/WADE model and used to project agricultural return flows to the San Joaquin River. These agricultural return flows provide input to the flow and water quality modules of DSM2-SJB and allow this model to calcu-

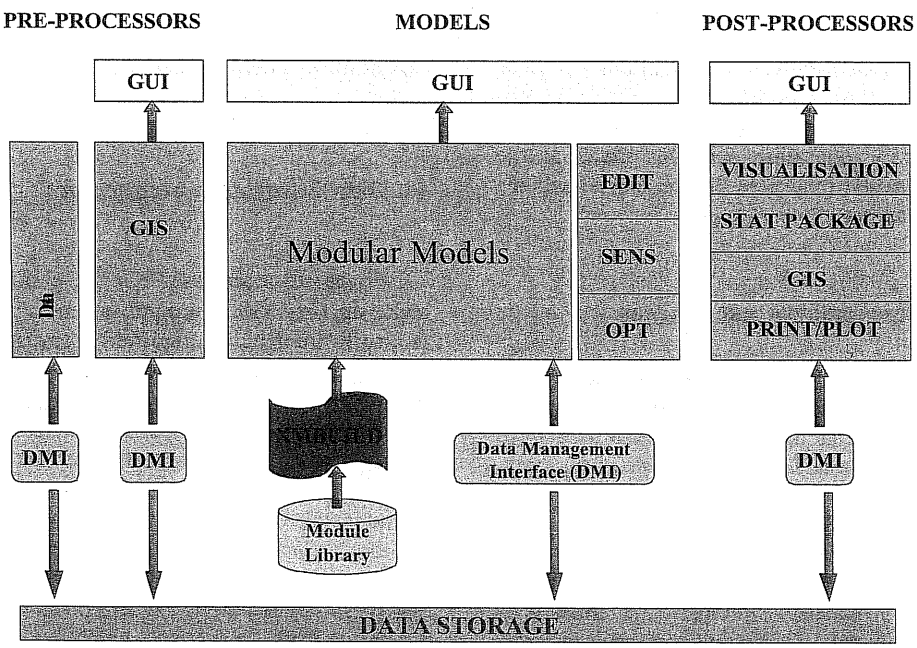

Fig. 3. Schematic of conceptual components of the Modular Modeling System (MMS) (Leavesley et al., 1996).

late river flow and environmental water quality that determine the suitability for fish — completing the feedback loop.

11. Summary

The DSS under development involves the integration of state-of-the-art resource management models newly developed within the State and Federal water agencies in California. The DSS is being designed with minimal time required for file manipulation to formulate impact response scenarios. The DSS should allow the analyst to assess the utility of interventions such as reservoir re-operation, real-time water quality management and adaptive management of fishery resources in mitigating some of the potential impacts of global climatic change and variability, hence reducing the vulnerability of the existing system to permanent damage. Training of the resulting DSS system will be provided to planners, operations analysts and other users to conduct further evaluations of the impacts of climate variability and extreme events and to develop approaches for the mitigation of potential impacts.

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